More Visible Effects of the Hidden Sector

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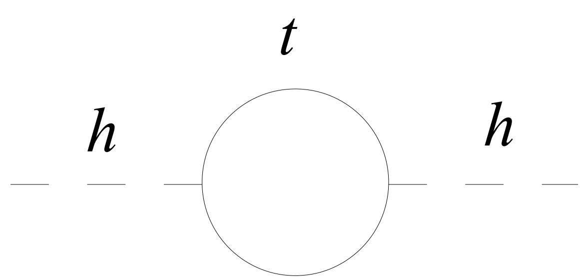
Outline

- Why supersymmetry?
- Meta-stable SUSY breaking
- Mediation => Higher dimensional operators
- Hidden sector dynamics
- Conformal hidden sectors
- Application to gauge mediation
  - Possible solution to μ (Bμ) problem!
- Things to do

Why Supersymmetry?

- The Standard Model suffers from a huge fine-tuning problem...
  - Quantum corrections to the Higgs mass parameter are *much* bigger than its value (set by weak scale)

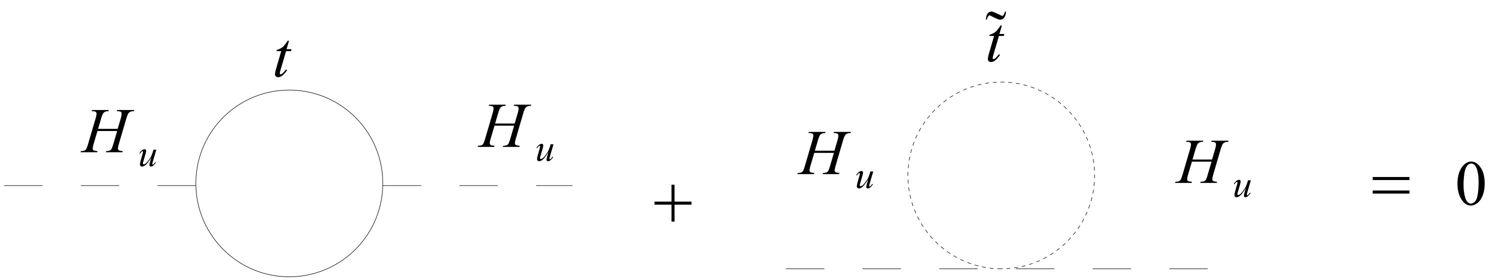


$$\approx -\frac{y_t^2}{16\pi^2}\Lambda^2$$

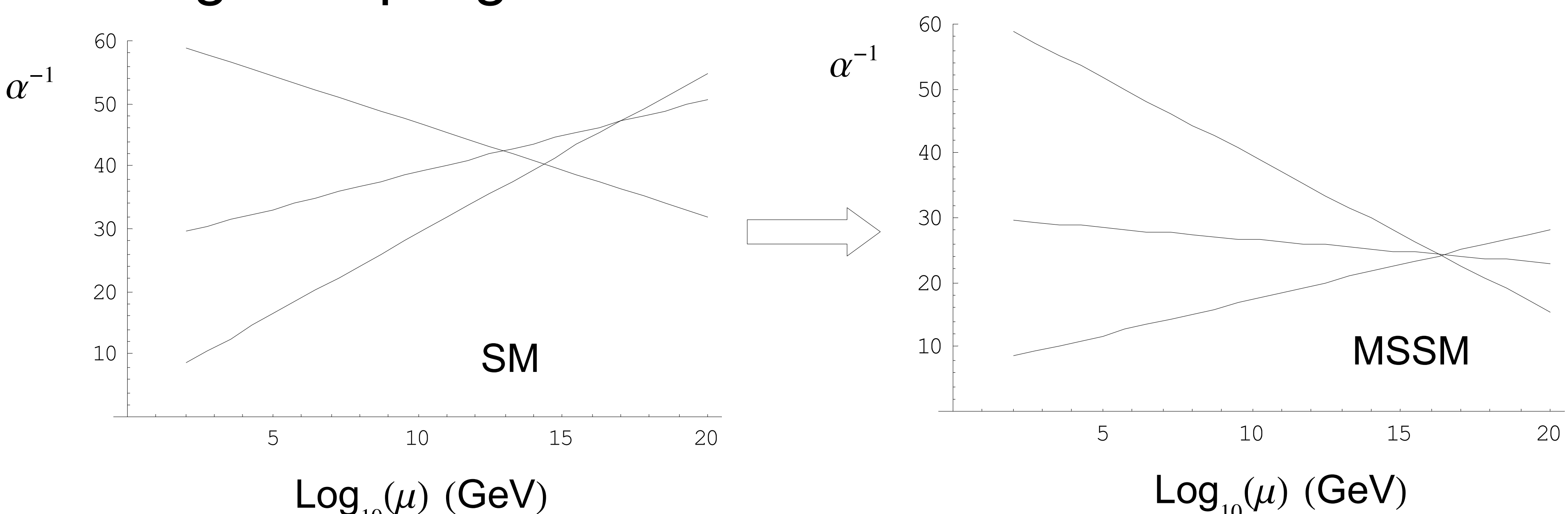
  - Not a problem for other SM particles
    - Fermion masses protected by chiral symmetry
    - Gauge bosons protected by gauge symmetry
  - Maybe we need a new symmetry!

Why Supersymmetry?

- Loops of superpartners cancel this divergence!



- Gauge coupling unification



There's just one problem...

- We haven't seen any superpartners in nature!
  - Supersymmetry must be *broken*
  - Scale of supersymmetry breaking should be close to weak scale to solve fine tuning problem... (LHC!)
  - This scenario is actually very exciting
    - The pattern of soft masses may tell us something about physics at very high scales!
      - Mediation mechanism
      - Grand Unification
      - SUSY breaking sector

How is SUSY Broken?

- Old way of thinking
  - Look for a theory with a SUSY breaking vacuum
  - Constrained by Witten index
  - Generic superpotentials require exact $U(1)_R$ symmetry [Nelson, Seiberg '93]
    - Must be spontaneously broken to generate gaugino masses
      - Leads to massless R-axion!
  - Can try explicit $U(1)_R$ breaking and a special, non-generic superpotential...
  - Life is difficult!

How is SUSY Broken?

- New way of thinking
  - We live in a meta-stable vacuum! [Intriligator, Seiberg, Shih, '06]
  - Can simply write down generic superpotential with broken $U(1)_R$ symmetry, vector-like matter, etc.
  - SUSY QCD with gives a simple example:
    - N_f vector-like quarks with $N_c < N_f < 3/2\ N_c$
    - Include mass terms $W = m_{ij} \overline{Q}^i Q^j$
    - Magnetic dual description: $SU(N_f - N_c)$ theory

$$W_{mag} = m_{ij} \Lambda S^{ij} + S^{ij} \bar{q}_i q_j + \text{non-perturbative}$$

    - SUSY broken at tree level because m_{ij} and $\bar{q}_i q_j$ have different rank: $F_S \neq 0$

The Hidden Sector

- Still need to communicate (meta-stable) SUSY breaking in a flavor blind way
  - Anomaly Mediation
  - Gauge Mediation
  - Gaugino Mediation
- Integrating out gauge/gravity messengers generates higher dimensional operators...

Higher Dimensional Operators

- Integrate out messengers...
  - Quadratic Operators:

$$\langle S \rangle = F_S \theta^2$$

$$\boxed{\int d^4\theta \frac{S^\dagger S}{M^2} \phi_I^\dagger \phi_I} \Rightarrow \text{Soft masses } m_I^2$$

$$\boxed{\int d^4\theta \frac{S^\dagger S}{M^2} H_u H_d} \Rightarrow B\mu - \text{term}$$

Higher Dimensional Operators

- Integrate out messengers...
  - Linear Operators:

$$\langle S \rangle = F_S \theta^2$$

$$\boxed{\int d^2\theta \frac{S}{M} W^{\alpha a} W^a_\alpha} \Rightarrow \text{Gaugino masses } M_a$$

$$\boxed{\int d^4\theta \frac{S^\dagger}{M} \phi_I^\dagger \phi_I} \Rightarrow \begin{array}{l} A-\text{terms } a_{IJK} \\ \text{Soft masses } m_I^2 \\ B\mu-\text{term} \end{array}$$

$$\boxed{\int d^4\theta \frac{S^\dagger}{M} H_u H_d} \Rightarrow \mu-\text{term}$$

A Simple Example...

- SUSY QCD with Gauge Mediation [Murayama, Nomura, '06]

$$W = -m_i \delta_{ij} \overline{Q}^i Q^j + \frac{\lambda_{ij}}{M_{Pl}} \overline{Q}^i Q^j \overline{f} f + M \overline{f} f$$

$$\Big\Downarrow$$

Seiberg Dual (Nc < Nf < 3/2 Nc)

$$W_{mag} = -\mu_i^2 S^{ii} + \lambda'_{ij} S^{ij} \overline{f} f + M \overline{f} f + a S^{ij} \overline{q}_i q_j$$

$$\Big\Downarrow$$

Integrate out messengers

$$L \sim \int d^2\theta \left(-\frac{1}{2} \frac{\lambda'_{ij}}{(4\pi)^2 M} \right) S^{ij} W_\alpha^a W^{a\alpha} + h.c.$$

$$+ \int d^4\theta \left(\frac{-2 C_I^a g_a^4 \lambda'^{\dagger ij} \lambda'_{kl}}{(4\pi)^4 M^2} \right) S_{ij}^\dagger S^{kl} \phi_I^\dagger \phi_I$$

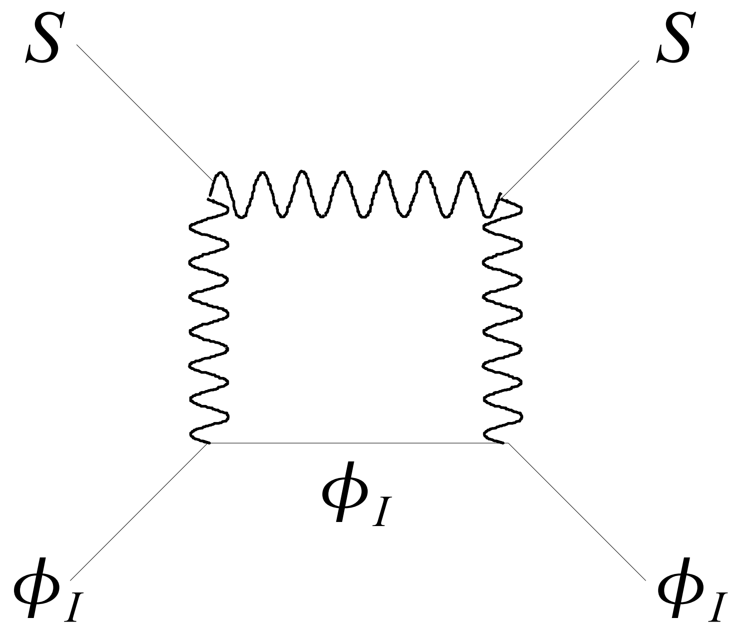
A few remarks

- This scheme is actually *very* generic!
  - From UV (string) theory, expect to have extra gauge groups and extra vector-like matter
  - Write down all allowed operators, and it is easy to get meta-stable SUSY breaking + gauge mediation!
  - Only need to satisfy certain inequalities

- We have generated the soft parameter operators at the messenger scale
  - Still need to run down to low energies!

The “Standard” Approach

- Calculate RGE running from visible sector interactions:



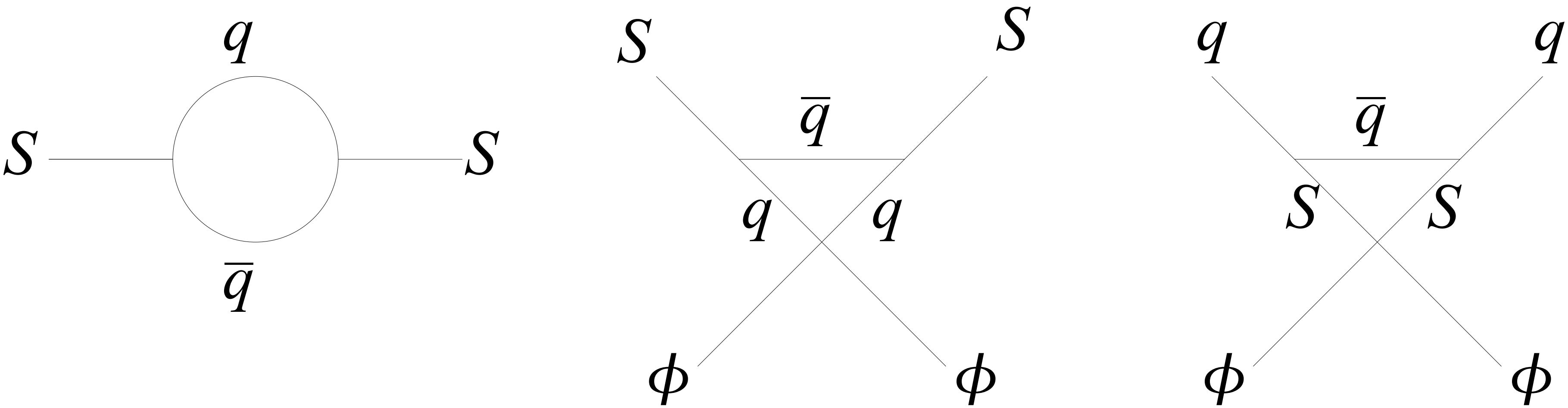
$$\frac{dK_I}{dt} = \frac{1}{(4\pi)^2} 8\, C_I^a\, g_a(t)^6\, \omega^\dagger \omega$$

- Run down to low energies
- Easily reversible...measure low scale soft parameters and run up to determine mediation mechanism
- But this isn't the complete story...

Hidden Sector Dynamics!

[Dine, et al, '04; Schmaltz, Cohen, Roy, '06]

- Hidden sector interactions like $W \sim S\,\bar{q}\,q$ also renormalize these operators:



- One way to proceed:
  - Simply calculate the perturbative effects in any given model (e.g., SQCD+Gauge Mediation)
  - *Perturbative* hidden sectors can lead to few % deviations from standard spectra...

Conformal Hidden Sectors

- What if the hidden sector is approximately conformal?
  - Effects can be much more dramatic!
  - Simple example: SUSY QCD with $3/2\ N_c < N_f < 3\ N_c$
    - Some flavors decouple at intermediate scale, and SUSY breaking happens as before
  - Partial results in 4D conformal sequestering...
    [Luty, Sundrum '01; Schmaltz, Sundrum '06]
  - However, situation with singlets and other mediation mechanisms had not been properly discussed
  - How are the linear and quadratic operators affected by conformal hidden sector dynamics?

Conformal Hidden Sectors

M_{PL}

Λ

M, Integrate out messengers

Conformal Window

m_X, Conformal symmetry breaks

F_S, SUSY breaks

m_W

Linear Operators

- Renormalized only through wavefunction renormalization
  - Determined by superconformal R-charge
  - Unitarity requires $R_S > 2/3$

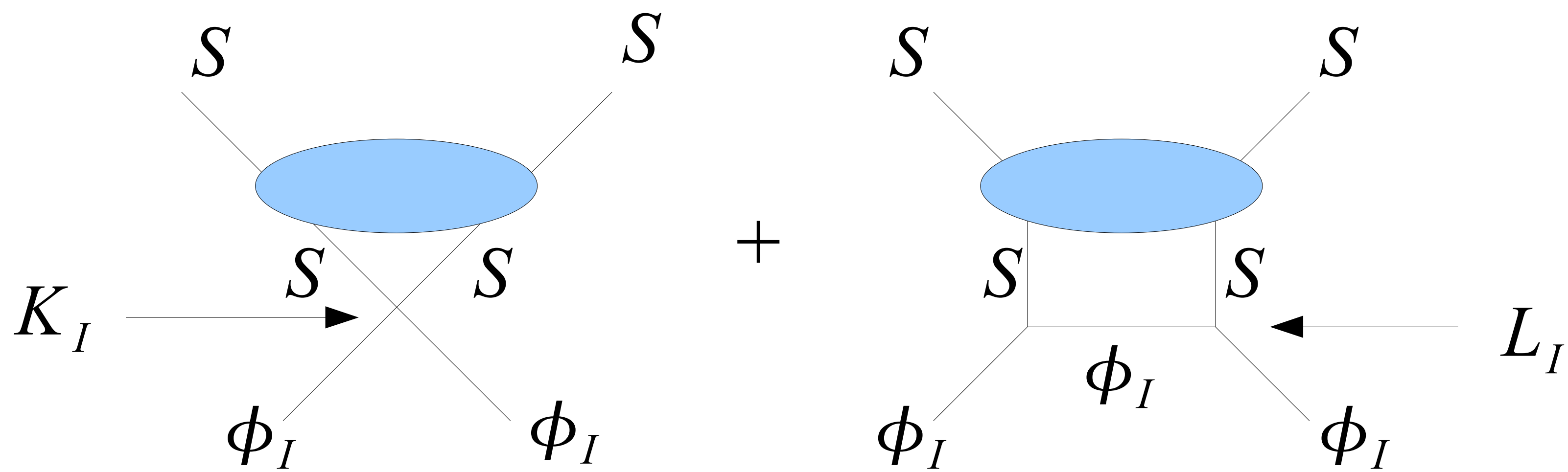
$$Z_S(\mu)=\left(\frac{\Lambda}{\mu}\right)^{3R_S-2}>1$$

$$\boxed{\int d^2\theta \frac{S}{M} W^\alpha W_\alpha} \Rightarrow \boxed{\int d^2\theta\, Z_S^{-1/2}(\mu) \frac{S}{M} W^\alpha W_\alpha}$$

- Same suppression factor for μ and A-term operators...

Quadratic Operators

- Also receive 1PI corrections:



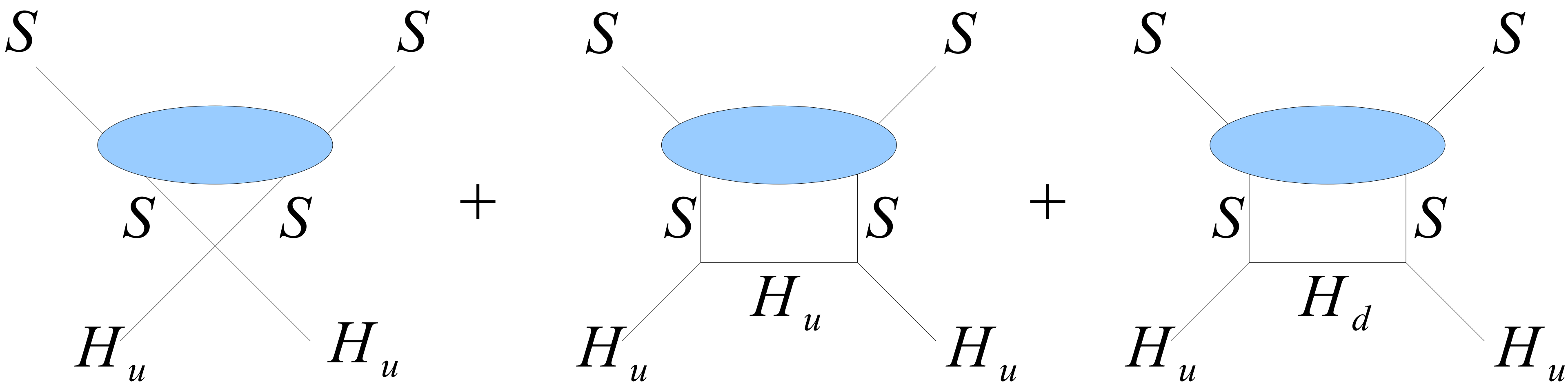
- Not possible in general to calculate, but expect:

$$\boxed{K_I - L_I^\dagger L_I} \Longrightarrow \boxed{\left(\frac{\mu}{\Lambda}\right)^{\alpha_S} Z_S^{-1}(\mu)(K_I - L_I^\dagger L_I)}$$

- May be more or less suppressed than linear operators
  - Depends on sign of α_S
- This is the combination that enters the soft masses m_I^2

Quadratic Operators

- The Higgs mass parameters also get renormalized through the mu-term operator:



- Combination that contributes to $m_H^2+\mu^2$ is suppressed
- Similarly, operator contributing to $B\mu$ is suppressed
- Can also mix with other *quadratic* operators like $q^\dagger q \phi^\dagger \phi$
  - Suppression controlled by largest eigenvalue of mixing $\hat{\alpha}_S$

Gravitino Mass

- Set by F-term VEVs in hidden sector after canceling cosmological constant:

$$m_{3/2} \sim \frac{F_S}{M_{Pl}}$$

- This should be compared to:

$$M_{linear} \sim Z_S^{-1/2}(\mu)\frac{F_S}{M}$$

$$M_{quadratic} \sim \left(\frac{\mu}{\Lambda}\right)^{\frac{\hat{\alpha}_S}{2}} Z_S^{-1/2}(\mu)\frac{F_S}{M}$$

- Soft parameters are all being suppressed *relative to* the gravitino mass!

Three Extreme Cases

- If the effects are strong, we might be led to one of three extreme situations:
  - Case 1: Linear Operator Dominance $(\hat{\alpha}_S > 0)$

$$\int d^2\theta\, Z_S^{-1/2} \frac{S}{M} W^{\alpha} W_{\alpha}$$

$$\int d^4\theta\, Z_S^{-1/2} \frac{S^{\dagger}}{M} \phi_I^{\dagger} \phi_I$$

$$\int d^4\theta\, Z_S^{-1/2} \frac{S^{\dagger}}{M} H_u H_d$$

$$m_I^2 = B = 0$$

$$m_{H_u}^2 = m_{H_d}^2 = -\mu^2$$

$$a_{IJK} = y_{IJK}(A_I + A_J + A_K)$$

$$M_a \approx \mu \approx A_I$$

Three Extreme Cases

- If the effects are strong, we might be led to one of three extreme situations:
  - Case 2: Quadratic Operator Dominance $(\hat{\alpha}_S < 0)$

$$\boxed{\int d^4\theta \left(\frac{\mu}{\Lambda}\right)^{\hat{\alpha}_S} Z_S^{-1}(\mu) \frac{S^\dagger S}{M^2} \phi_I^\dagger \phi_I} \qquad \boxed{\int d^4\theta \left(\frac{\mu}{\Lambda}\right)^{\hat{\alpha}_S} Z_S^{-1}(\mu) \frac{S^\dagger S}{M^2} H_u H_d}$$

$$\boxed{m_I^2, B\mu \gg M_a^2, \mu^2, a_{IJK}^2}$$

  - Led to a split spectrum...

Three Extreme Cases

- If the effects are strong, we might be led to one of three extreme situations:
  - Case 3: Anomaly Mediation Dominance

$$\frac{m_{3/2}}{16\pi^2} \gg M_{linear}, M_{quadratic}$$

    - Happens when both kinds of operators are suppressed enough relative to the gravitino mass
    - Conformal sequestering can work with singlets!
    - Solves flavor, but still have to worry about tachyonic sleptons, too large Bμ, etc...

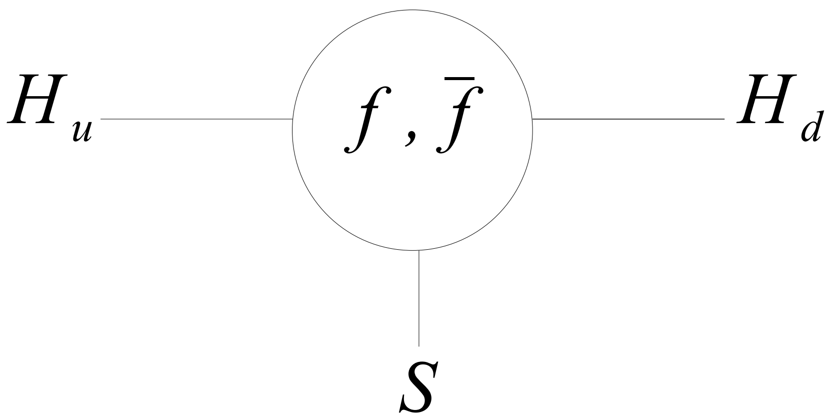
Gauge Mediation

- What happens when we apply this to *gauge mediation*?
  - Case 1
    - Can solve the μ ($B\mu$) problem!
    - Resembles low-scale gaugino mediation (with A-terms and funny Higgs sector)
  - Case 2
    - Spectrum with *fractional* number of messengers

μ (Bμ) Problem in Gauge Mediation

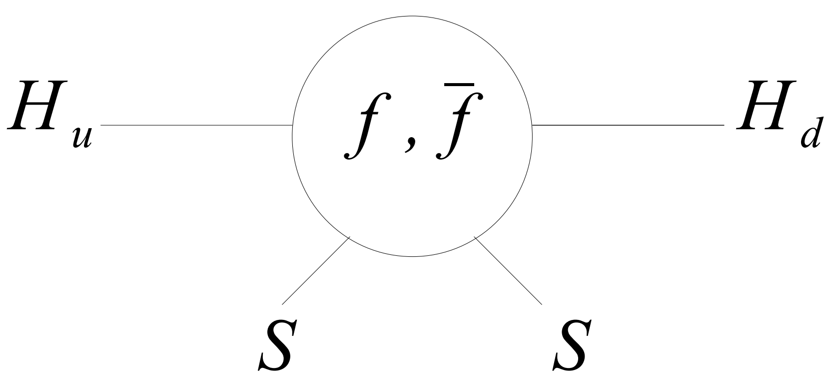
- When we try to generate μ at one loop...

$$\left(\text{e.g.,}\ W = y\, f\, f\, H_u + \bar{y}\, \bar{f}\, \bar{f}\, H_d\right)$$



$$\sim \frac{y\,\bar{y}\,\lambda}{16\pi^2 M} S^\dagger H_u H_d$$

- We generically also generate Bμ at one loop!



$$\sim \frac{y\,\bar{y}\,|\lambda|^2}{16\pi^2 M^2} S^\dagger S\, H_u H_d$$

A Possible Solution... (Case 1)

[See also: Roy, Schmaltz '07]

- Hidden sector dynamics suppresses Bμ relative to μ!
  - Scalar masses disappear...
  - Gaugino masses still same form $M_a \sim \frac{g_a^2}{16\pi^2}\left(\frac{F}{M}\right)_{eff}$
  - Higgs A-terms come from dynamics generating μ

- Spectrum at intermediate scale looks like:

$$m^2_{Q_I, U_I, D_I, L_I, E_I} = 0$$

$$(a_u)_{IJ} = (y_u)_{IJ} A_{H_u}, \qquad (a_d)_{IJ} = (y_d)_{IJ} A_{H_d}, \qquad (a_e)_{IJ} = (y_e)_{IJ} A_{H_d}$$

$$m^2_{H_u} = -\mu^2, \qquad m^2_{H_d} = -\mu^2, \qquad B = 0$$

$$M_a \approx \mu \approx A_{H_u} \approx A_{H_d}$$

Split Gauge Mediation (Case 2)

- Gaugino masses suppressed relative to scalars, but form stays fixed:

$$M_a = N_{mess} \frac{g_a^2}{16\pi^2} \left(\frac{F}{M} \right)_{eff}$$

$$m_I^2 = 2 N_{mess} C_I^a \left(\frac{g_a^2}{16\pi^2} \right)^2 \left| \left(\frac{F}{M} \right)_{eff} \right|^2$$

- Looks like N_{mess} is *fractional*!
- Requires fine-tuning in Higgs sector, but may still be interesting if splitting is not so large...

Things to do...

- Study the sequestered spectrum!
  - Very predictive
  - Naively looks great from tuning perspective
  - However, a bit tricky to make EWSB work
- Find a candidate hidden sector with a calculable limit
  - Unfortunately SUSY QCD in Banks-Zaks limit does not give correct signs for anomalous dimensions...
- Dark Matter
  - Non-gravitino LSP in gauge mediation
- Study inverse problem
  - e.g., how to distinguish between hidden sector dynamics and complicated messenger sector?